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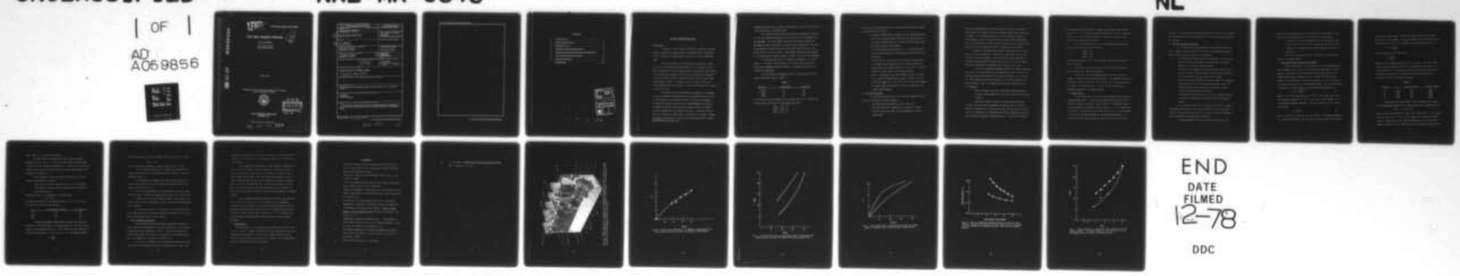

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NRL Memorandum Report 3848

AD A059856

CGE Rod Amplifier Modules

John M. McMahon

Laser Physics Branch
Plasma Physics Division

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August 1978

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	NRL Memorandum Report 3848
2. GOVT ACCESSION NO.	
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle)	6 CGE ROD AMPLIFIER MODULES.
5. TYPE OF REPORT & PERIOD COVERED	Interim report on a continuing NRL problem.
6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s)	10 John M. McMahon
8. CONTRACT OR GRANT NUMBER(s)	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	Naval Research Laboratory Washington, D. C. 20375
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	NRL Problem H02-29A
11. CONTROLLING OFFICE NAME AND ADDRESS	U. S. Department of Energy Washington, D. C. 20375
12. REPORT DATE	11 August 1978
13. NUMBER OF PAGES	22
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	12 22p.
15. SECURITY CLASS. (of this report)	UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

14 NRL-MR-3848

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Work performed at the Naval Research Laboratory under the auspices of the U. S. Department of Energy.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Rod amplifier
Neodymium glass laser

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The performance and development history of the neodymium glass laser rod amplifiers in use at NRL on the Pharos II laser system is reviewed. The impact of possible future modifications is assessed.

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CGE ROD AMPLIFIER MODULES

Introduction

The Pharos II laser system at NRL uses a number of helically pumped rod amplifier modules which were purchased from the Companie Generale d'Electricite (Marcoussis, France) in the time frame 1968-1971.

The initial design of these modules was performed in 1966 and 1967 for Soveril MG 915 laser glass.[1,2,3] The various sizes of CGE rod amplifiers use flash lamps which are electrically very similar i.e., as the major diameter of the helix is increased for larger rod sizes the number of turns is reduced such that the arc length stays approximately constant. For purposes of this study we will use average parameters of arc length, l, equal to 120 cm and bore diameter d, equal to 1.0 cm.

The definitive study by Markiewicz and Emmett on flashlamps as circuit elements was published after the CGE modules were tested,[4] so the designers did not have the benefit of using this analysis. The approach that was followed was to experimentally test possible flashlamp modules and make the design choices based on a tradeoff between flashlamp life and pumping efficiency. Lifetime was determined by conducting lifetime tests as a function of loading. Pumping efficiency was modeled by integrating the lamp output with a "leaky"

Note: Manuscript submitted August 7, 1978.

integrator whose RC time constant would simulate the fluorescence decay of the laser decay of the laser glass.

The "typical" module derived from these measurements consisted of a 140 μfd capacitor charged at up to 12 kV and then discharged into the flashlamp. A series trigger transformer was used to trigger the flashlamp and also to provide most of the circuit inductance. The lamp was connected to the bank using two cables which were similar to the center conductor of RG - 8 cable. The trigger transformer would supply a 4 μs duration pulse with a voltage in excess of 30 kV to the flashlamp.

A cross-sectional view of a typical rod amplifier is shown in Figure 1. The laser rod was mounted in a co-axial water jacket with the helical flashlamps around the jacket. An aluminum reflector surrounded the flashlamps.

The rod lengths and diameters used in the amplifiers still in service at NRL are listed in table I:

Table I

Amplifier	diameter(mm)	length(mm)
V23A2	23	320
V32A4	32	460
V45A4	45	460

With Soveril MG 915 laser glass or the similar Schott LG - 56 glass the on-axis small signal gains of these amplifiers were:

$$V23A2 - e^{\alpha Z} = 18$$
$$V32A4 - e^{\alpha Z} = 22$$
$$V45A4 - e^{\alpha Z} = 9$$

In general these amplifiers were well behaved and reliable but a number of peculiarities were noted:

- occasional catastrophic flashlamp failure, apparently caused by the high voltage trigger "punching" through weak spots in the quartz envelope arcing to a ground with subsequent bank discharge along the same channel.
- while flashlamp life expectations of 5 - 10,000 shots were met there was darkening of the envelope caused by electrode sputtering.
- a short service life for the 3C45 thyratron tubes driving the trigger transformers and also the ignitron switches.
- large ground loop currents caused by the use of two discrete cables per module rather than co-axial cabling.
- when the laser glass type was switched to Owens - Illinois ED - 2 with an induced emission cross - section of 2.7×10^{-20} cm^2 compared to $\sim 1.8 \times 10^{-20}$ cm^2 for the other glasses the small signal gain coefficient did not increase at the highest pump energies.

2. Prior Modifications

The electrical reliability of the units was improved by modifying the circuitry in several respects;

- the ignitron was replaced by a more robust unit.
- the load cables were replaced by a single RG - 8 cable.
- a grounded wire was added to the flashlamps to define a ground plane.

With these modifications it was not necessary to pulse the trigger transformer as the lamps would fire by simply switching the banks into the lamps. This allowed elimination of one thyratron per module. Additionally, in the original circuit the series trigger transformer was in the ground leg, so both sides were floating; the transformer was moved to the high voltage side where it functions as an inductor.

Lamps with electrodes which show no sputtering were obtained from ILC Inc., Sunnyvale, Ca. These have a much longer service life than the original CGE lamps. A set of experiments was performed in 1972 which indicated that the reason that ED - 2 did not give higher gains was that parasitic oscillation was occuring in the rods.

In the first experiments aqueous solutions of Samarium Chloride were used in the water jackets of an amplifier to raise the index of refraction and give absorption at the laser wavelength. The threshold vs. index mismatch allowed identification of the offending mode as a radial "whisper" mode. The Samarium Chloride solutions however had two drawbacks:

- while the small signal gain coefficient was approximately doubled, clearly parasitics were still occuring above $\frac{2}{3}$ pump energy.
- high index Samarium solutions were extremely corrosive.

The work of Dube and Boling suggested that $ZnCl_2$ might be a better choice as a material for increasing the index of the liquid around the rod.[5] By a combination of experiment and kitchen chemistry a solution was found which suppressed radial parasitics. It was also necessary to

anti-reflection coat the rods to suppress "organ pipe" modes at high gain levels.[6] Good stability has been obtained in conditions where the materials in contact with the fluid are restricted to glass, nylon, Tygon tubing and gold plated metal.

By use of these solutions and Ar coatings the small signal gain coefficients have been increased to:

V23A2 - 50
V32A4 - 120
V45A4 - 30

These values represent a 40 - 55% increase in the stored inversion or gain coefficient.

Experience over the past four years with the CGE modules in this state has been generally excellent.

There have been few flashlamp failures and all have been failure to trigger rather than lamp breakage. At irregular intervals on the order of once a year the rod end fittings must be replated because of attack by the $ZnCl_2$ solution. At that time the water jacket is generally replaced and the lamps cleaned.

3. Present Status

In the near future the entire laser system will be converted to phosphate laser glass. To achieve wavelength matching Nd:Ylf will be used in the master oscillator. Rods of Kigre Q - 88 phosphate glass have been obtained of acceptible optical quality ($\lambda/10$ in transmission at 1.054 μm). A lower doping was chosed than for ED - 2 silicate glass to achieve flatter spatial **profiles.** Preliminary measurements on an uncoated 45 mm rod indicate that the gain at 1.064 mm is the same as

with ED - 2. These results indicate that at least a factor of 1.6 larger gain coefficient will be achieved after the rods are coated and operated at 1.054 μm.

4. Possible Future Modifications

A. One modification which might be desirable would be to convert to capacitor banks similar to the present disk amplifier modules. Several factors argue in favor of this approach:

- the CGE capacitor bank modules were designed a long time ago for a different laser glass and a fresh approach might be expected to yield improved performance.
- a number of the capacitor banks have 20,000 - 25,000 shots. No overt signs of an end-of-life situation have been noted but at some point this may become a real problem.
- the laser control electronics could be simplified if capacitor banks similar to the disk amplifier banks were used. The present control system represents a compromise between several different design philosophies.
- disk amplifier banks have been in use for a number of years on the 30 ns system used in 6700 which uses CGE amplifier heads.

B. A second modification which has merit would be to replace the present water jackets with a tube treated by the Corning process to have very low surface reflection.[7,8] This would have several advantages from a performance and maintenance standpoint:

- the $SmCl_2$ absorber could be removed from the $ZnCl_2$: H_2O

solution as the parasitics would be stabilized for any angles of incidence which would correspond to a path through the gain medium.

- in addition to reducing attenuation of the flashlamp light by 4% or more at the interface between air and water jacket, removal of the samarium would improve pumping efficiency by about 10%.

In the next two sections we will consider each of these modifications in greater detail.

5. Driving CGE modules with NRL Disc Modules

As was noted earlier in this report, the CGE flashlamp modules were developed before a model for the electrical properties of flashlamps was developed.[4] In-house experience indicates superior life-loading characteristics compared to the original CGE lamps largely because of the development of electrodes which do not cause sputtering of electrode material onto the flashlamp envelope. The theory developed in Reference 4 relates capacitor bank and flashlamp parameters as

$$C^3 = 2Eo \left(\frac{\alpha}{Ko}\right)^4 T^2 \qquad -1-$$

where C is the bank capacitance, $Eo = \frac{1}{2} CV^2$ is the stored energy with V the charging voltage, and $T = \sqrt{LC}$ is the circuit time constant. Ko is the flashlamp impedance parameter. For the pressures of Xenon used in these lamps

$$Ko = \frac{4}{3} \frac{l}{d} \qquad -2-$$

where l is the arc length and d is the diameter. The damping parameter, α, is given by Reference 4 as 0.8, but as 0.84 by a more recent study.[9]

Circuits with lower values of α will ring while circuits with higher values will be over-damped. The study in Reference 4 showed little real sensitivity for $.8 < \alpha < 1.2$. Equation 1 can be manipulated to give

$$\alpha = Ko\ [\frac{C}{\sqrt{L}}]^{\frac{1}{2}} \qquad -3-$$

For the parameters of the CGE circuit

$$\alpha = \frac{1.34}{(x)^{\frac{1}{2}}}$$

where x is the charging voltage in tens of kilovolts. For most values of the charging voltage the circuit is substantially over damped. We can use Reference 4 to estimate the fraction of the bank energy which is useful as a function of voltage by estimating what fraction is delivered in 600 μs, the time to peak gain.

Table I

Voltage	α	useful fraction	useful energy(J)
8	1.49	.83	3700
9	1.41	.86	4840
10	1.34	.88	6110
11	1.28	.89	7480
12	1.20	.93	9300

Trenholme has recently reported that the transfer efficiency of flashlamp pumping cavities to neodymum glass can be approximated by[10]

$$\epsilon = \frac{A}{J^n}\ (\ 1 - \exp - BJ) \qquad -4-$$

where J is the current density, A and B are constants and n is a constant with the value $0.8 < n < 1.0$. If we compare the achieved gain coefficient vs. pump energy for the CGE V45A4 amplifier (Fig. 2) to these models we obtain $n = .46$ in Equation 4 without using the correction from

table I and n = .63 using the correction.

The fact that this disagrees with the fitting parameters Trenholme found of $0.8 < n < 1.0$ would indicate that the losses might be worse than was estimated from Reference 4. The recent work reported in Ref. 9 also found that losses affect the circuit more strongly that estimated in Reference 4.

We can attempt to infer the losses as a function of current density by assuming the following:

- the cavity efficiency will scale as $Ec = J^{-\frac{1}{2}}$ (for large J)
- the overall efficiency will be a product of electrical and cavity efficiencies.

Since Ohm's law for a flashlamp can be expressed as:

$$V = Ko\ (j)^{\frac{1}{2}}$$

The power and energy into the Lamp will scale as $j^{\frac{3}{2}}$. If we set E_E = .9 at 10kJ we find for selected values

E	Electrical Efficiency	E_E (ref. 4)
5kJ	.79	.85
7.5kJ	.88	.88
10kJ	.90	.93

It appears reasonably credible that the reason for the poor efficiency of the CGE modules at low pump energy is significant circuit losses in the overdamped circuits. If the CGE module were replaced by a disc laser module with C = 42 μfd and T = μs , the damping constant

$$\alpha = \frac{.97}{[x]^{\frac{1}{2}}}$$

and full bank energy (8.4kJ) is reached at 20 kV not 12. As a result,

$$\alpha_{(20)} = .70$$

which is slightly underdamped. At half energy 14 kV, $\alpha = 0.83$.

The more recent Rochester work[9] suggests that the effect of circuit losses will be to increase the effective damping so these are reasonable values of α.

The increased peak voltage will lower cavity transfer efficiency by just about the same factor that the shorter pulse will decrease the fluorescence loss.

The circuit improvements should boost that efficiency, hopefully by enough to offset the decreased bank energy (8.4 kJ from 10 kJ).

Figures 3 and 4 show the expected change in gain and gain coefficient with CGE and disk modules. Fig's 5 and 6 show another aspect of this change.

The conclusion is that it is possible to drive the CGE heads with disk modules more efficiently than with CGE modules but it is not obvious that higher gains will be achieved.

6. Use of Treated Pyrex Tubing

The Corning Glass Works has recently disclosed a process by which Pyrex can be treated such that the reflectivity of the surfaces is markedly reduced (References 7 and 8). This process produces a surface which has an initial index of refraction of 1.12 which grades up to the normal index of Pyrex over a 5000 Å zone.

The result is equivalent to a broad bank anti-reflection coating but has some properties which such a coating does not have. The

reflectivity is quite low for a variety of angles of incidence up to 70° because this process causes an index gradient rather than operating by interference.

Such a material would appear to offer substantial advantage if used as the water jacket around the laser rod. Presently, ordinary Pyrex tubes are used. The liquid is not water but a witches' brew of water, $ZnCl_2$, HCl and $SmCl_2$ which has the desirable properties that it nearly index matches the laser rod and stabilizes a parasitic whisper mode in the rod. The Samarium salt is required to suppress a whisper mode in the water jacket. The undesirable feature of this liquid is that it is very corrosive and over the long term approximates a universal solvent.

Use of treated Pyrex would stabilize this particular mode without the need for recourse to a 1 μm absorber; hence the Samarium Chloride could be eliminated. This would virtually eliminate the maintenance problems associated with use of the index matching fluid; additionally it would boost the gain coefficient by $\sim 15\%$. The pump light would be coupled more efficiently and there would be lower internal absorption.

7. Acknowledgment

The improvements to the CGE amplifier modules have occurred over a period of years. A number of present and former NRL employees have made substantial contributions to this effort including Orville C. Barr, Robert P. Burns, Thomas H. DeRieux, John L. Emmett, John F. Holzrichter, Jules P. Letellier and John B. Trenholme.

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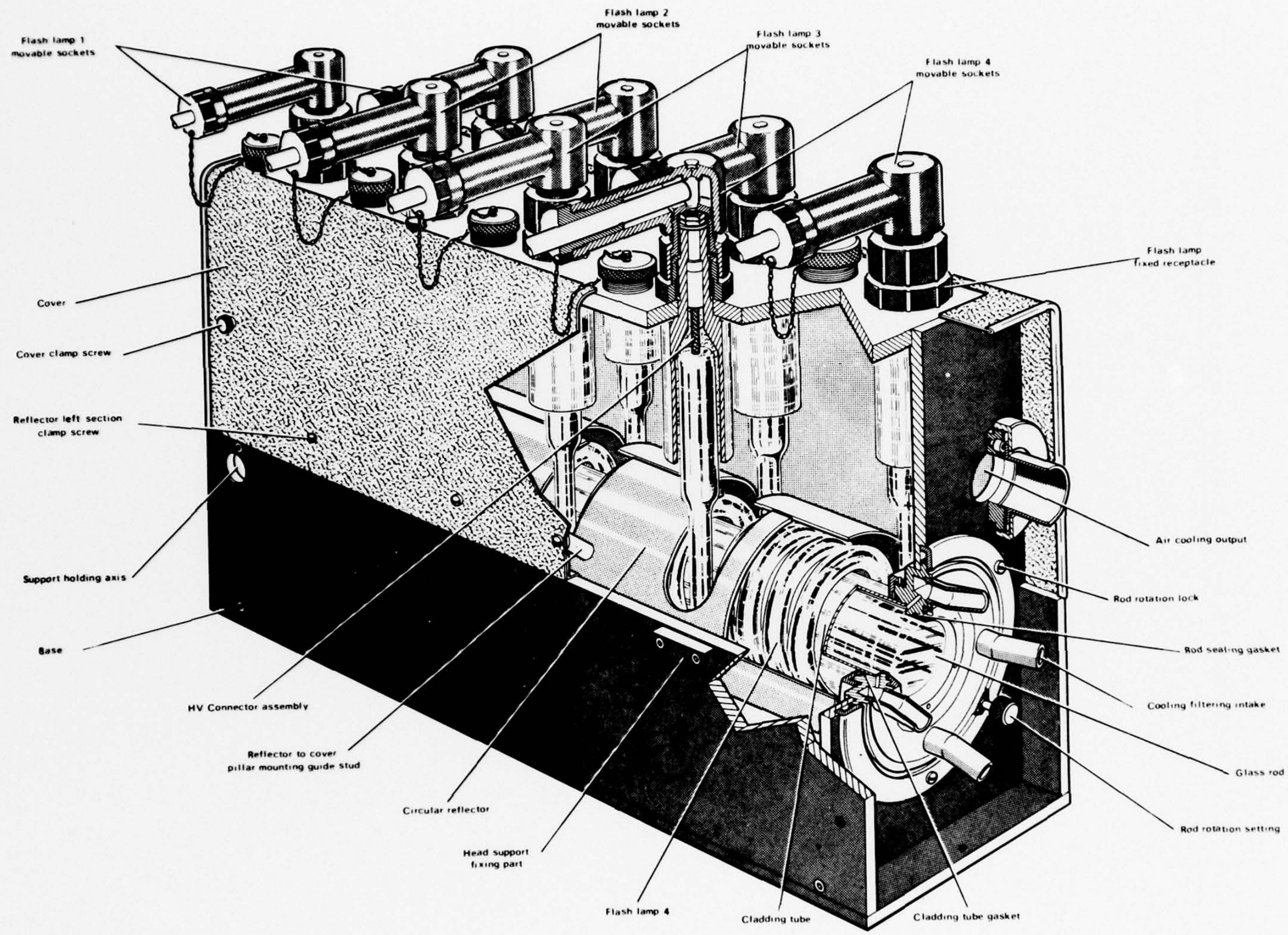

Fig. 1 - Cutaway drawing of a typical four flashlamp CGE amplifier module such as the V45A4 or V32A4. The laser rod is surrounded by a concentric water jacket; this assembly fits inside the helical flashlamps and their reflectors.

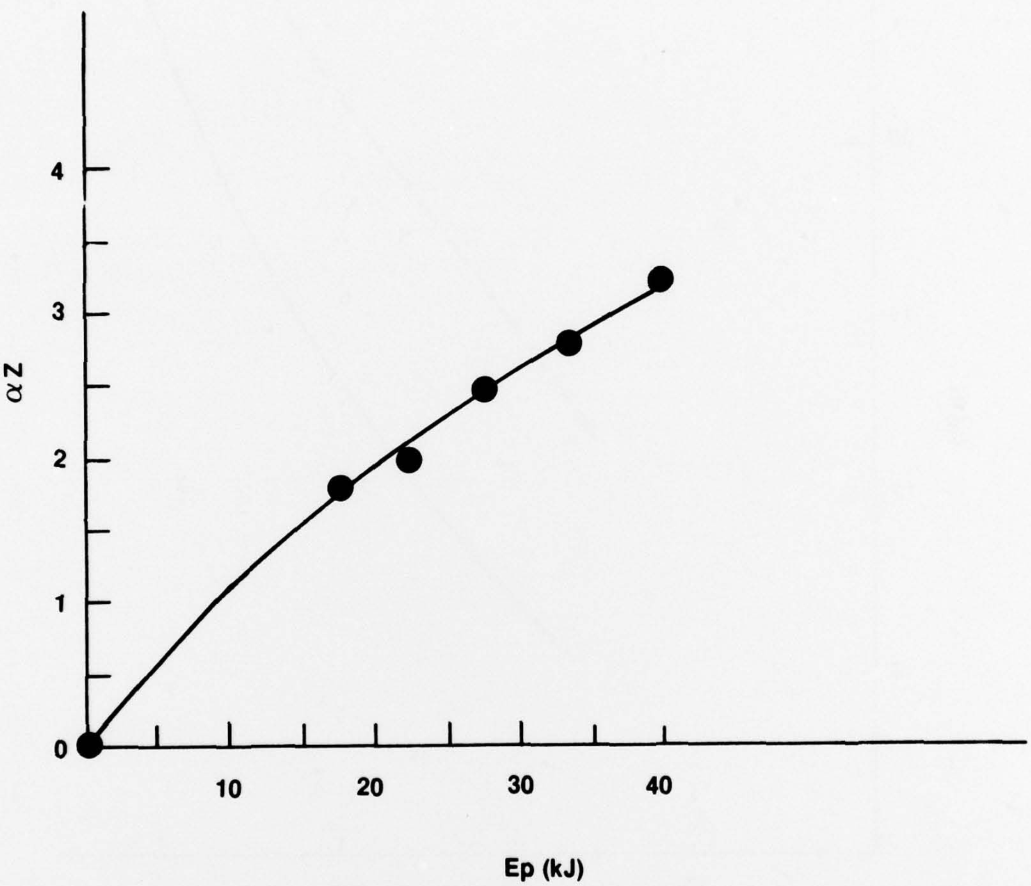

Fig. 2 - On-axis gain coefficient at 1.064μm vs. pump energy for a V45A4 amplifier with ED-2 glass and parasitic stabilization.

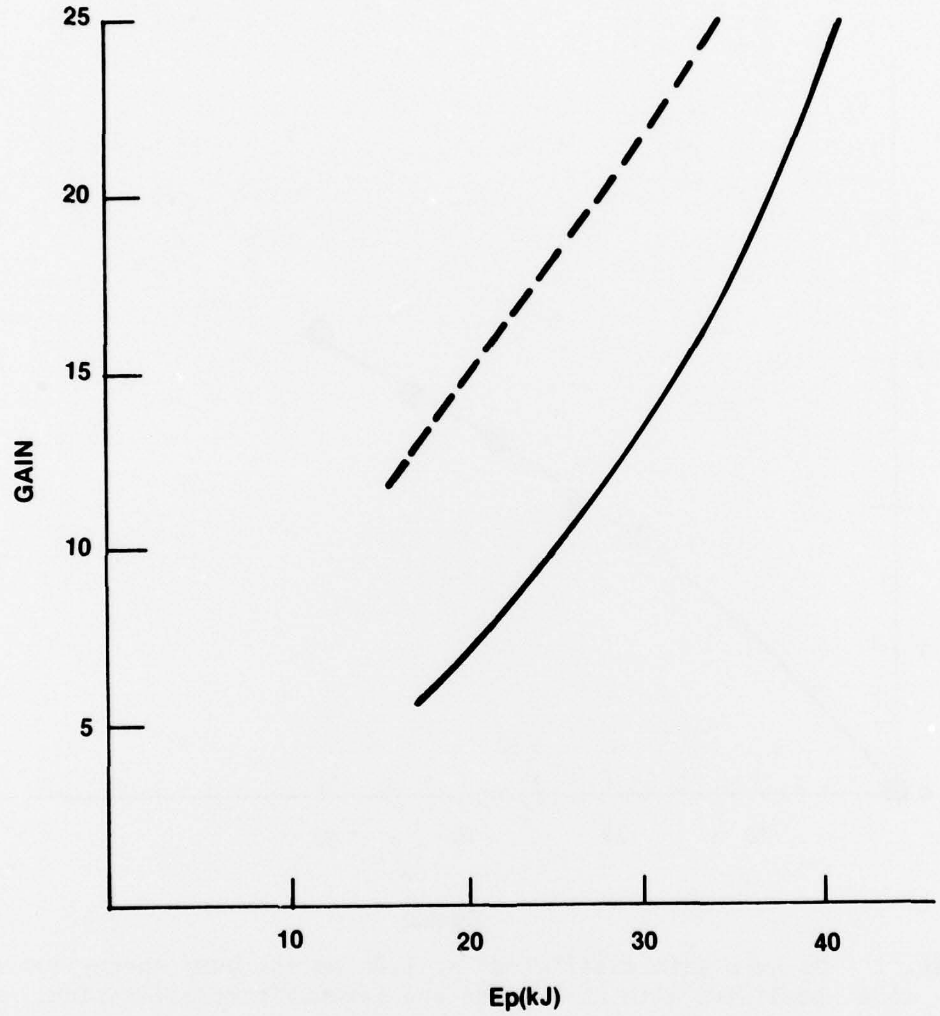

Fig. 3 - Prediction of gain vs. pump energy using the standard pump modules (solid line) and disc amplifier modules (dashed line).

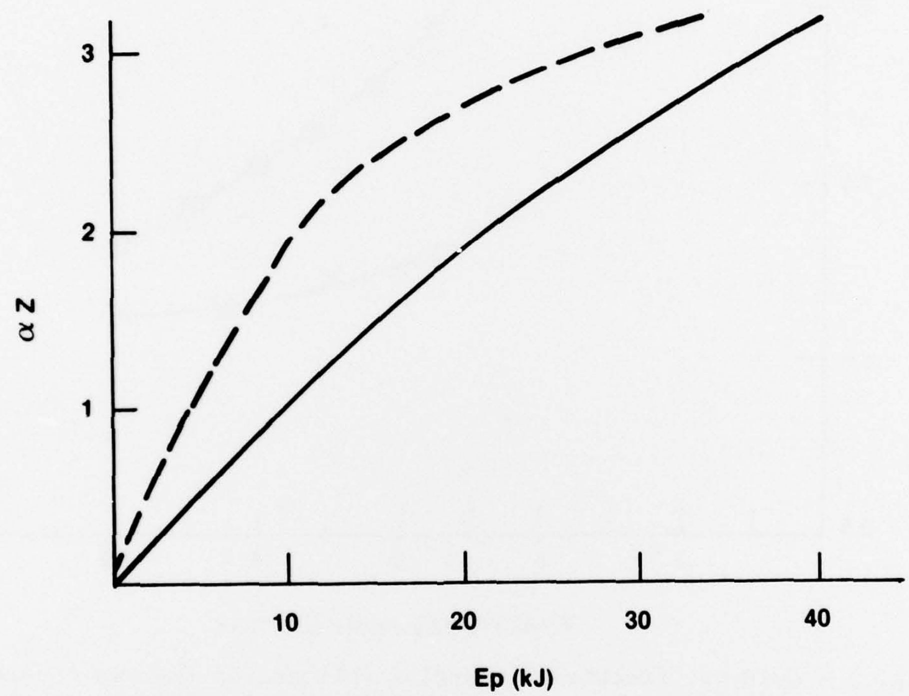

Fig. 4 - Gain coefficient vs. pump energy with the two module choices; standard (solid curve) and disc (dashed curve).

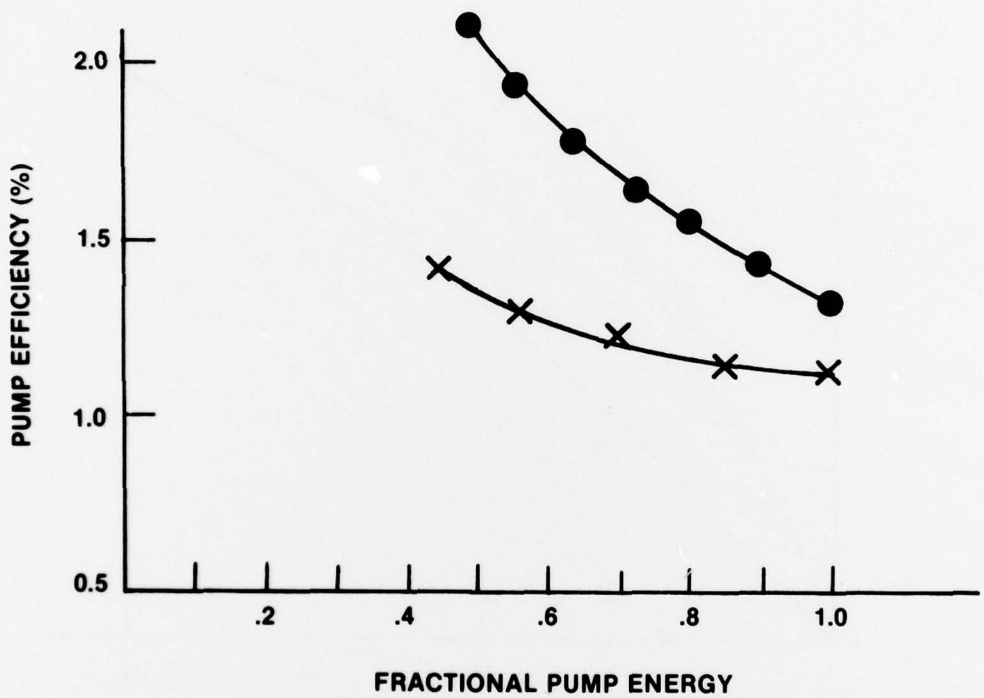

Fig. 5 - Gain vs. fractional charging voltage for the two module choices. The gain achieved with the disc module would be considerably less sensitive to charging precision than with the standard module.

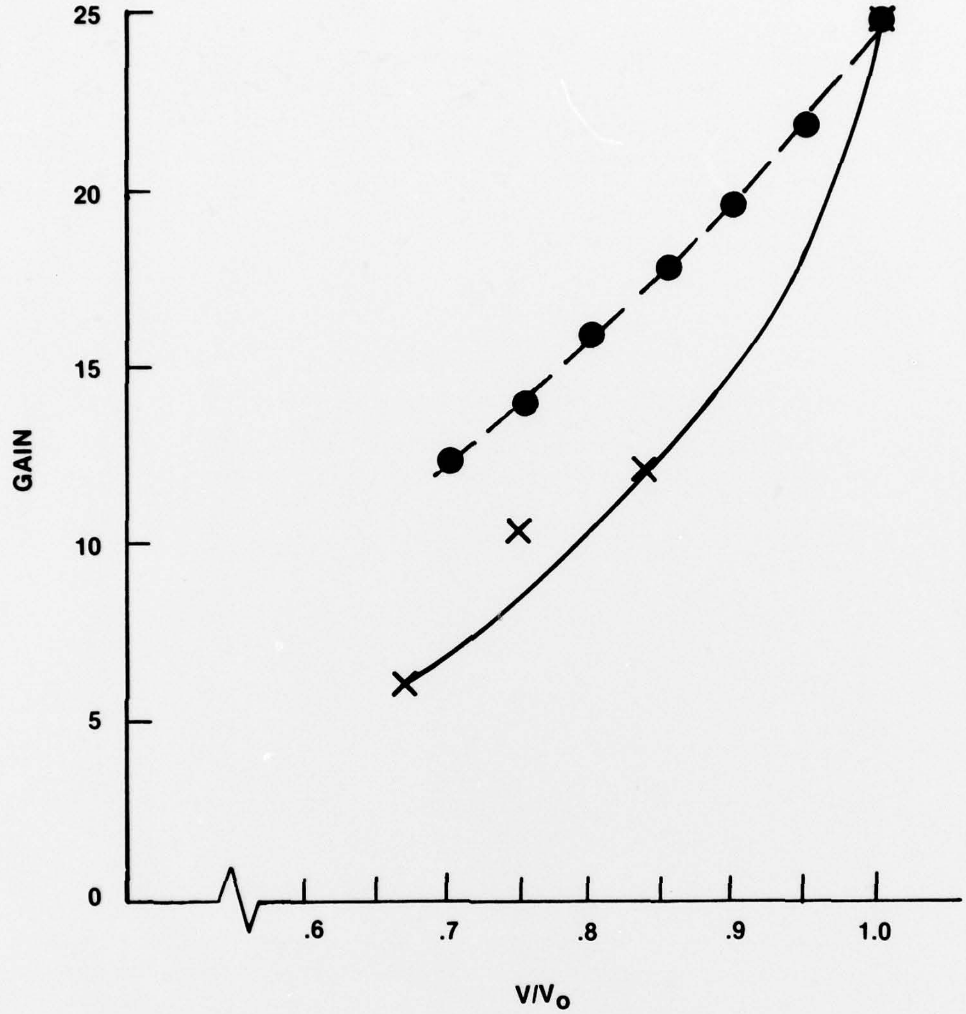

Fig. 6 - Pump efficiency vs. fractional bank energy for the two pumping modules. The rapid decrease in the efficiency of the disc module case is caused by flashlamp opacity.